Failure Forensics and Re-Design of Reversible Flow Draft Tube Trash Racks at a Pumped-Storage Plant

by

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Abstract

This paper documents the resolution of trash rack failures in the lower pool draft tube trash racks for Ameren Missouri's two-unit, 450 MW Taum Sauk Pumped-Storage Plant. During clean out of the tail race, portions of the steel draft tube trash racks were found in the tail race. Engineering support was provided by HPPi and HDR to incorporate and analyze new design features in the replacement trash rack design. Subsequent in place inspections since the new trash racks have been returned to service in 2010 have shown no indications of cracking or degradation.

Background

Ameren Missouri's Taum Sauk Pump-Storage Plant has two units, each rated at 225 MW. Trash racks are located at the exit of the draft tubes in the tail race of the lower reservoir. Each unit has a draft tube with dual exits (see Figure 1), and each trash rack slot contains a single steel trash rack at the draft tube exits with four timber racks on top (see Figure 2). During clean out operations of the tail race in 2006, portions of the steel draft tube trash racks were found in the tail race. Further inspection revealed that a similar portion of the draft tube trash racks was missing for each unit. The missing section occurred in the left trash rack of each unit and was the lower half of the steel rack.

Plant maintenance records documented a similar failure which occurred several years earlier, when detached trash rack sections were discovered during an outage inspection. The trash racks were replaced at that time with racks of the original design. The actual time of failure could not be determined, but the failure probably occurred after the pump-turbines were replaced with higher capacity runners in 1998 and 1999. In addition, single bar failures were reported for Taum Sauk in the 1960s [ASCE, 1993].

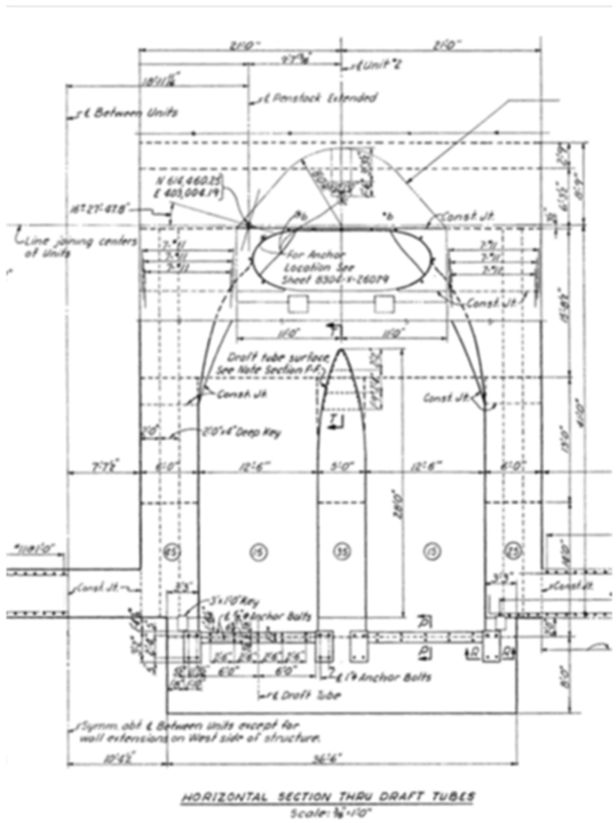


Figure 1: Draft Tube Arrangement for Each Unit

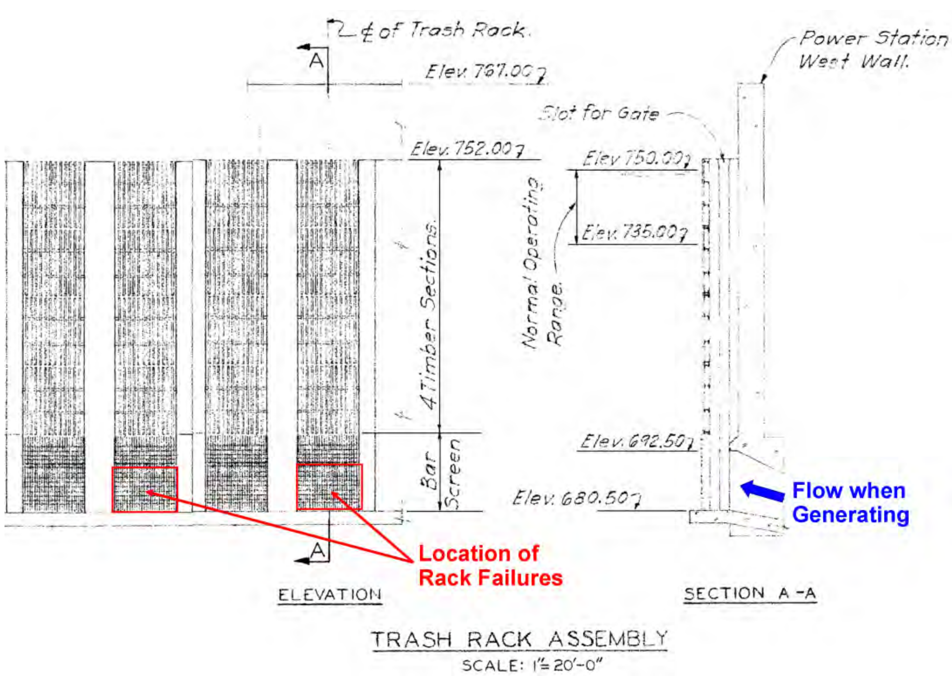


Figure 2: Trash Rack Arrangement

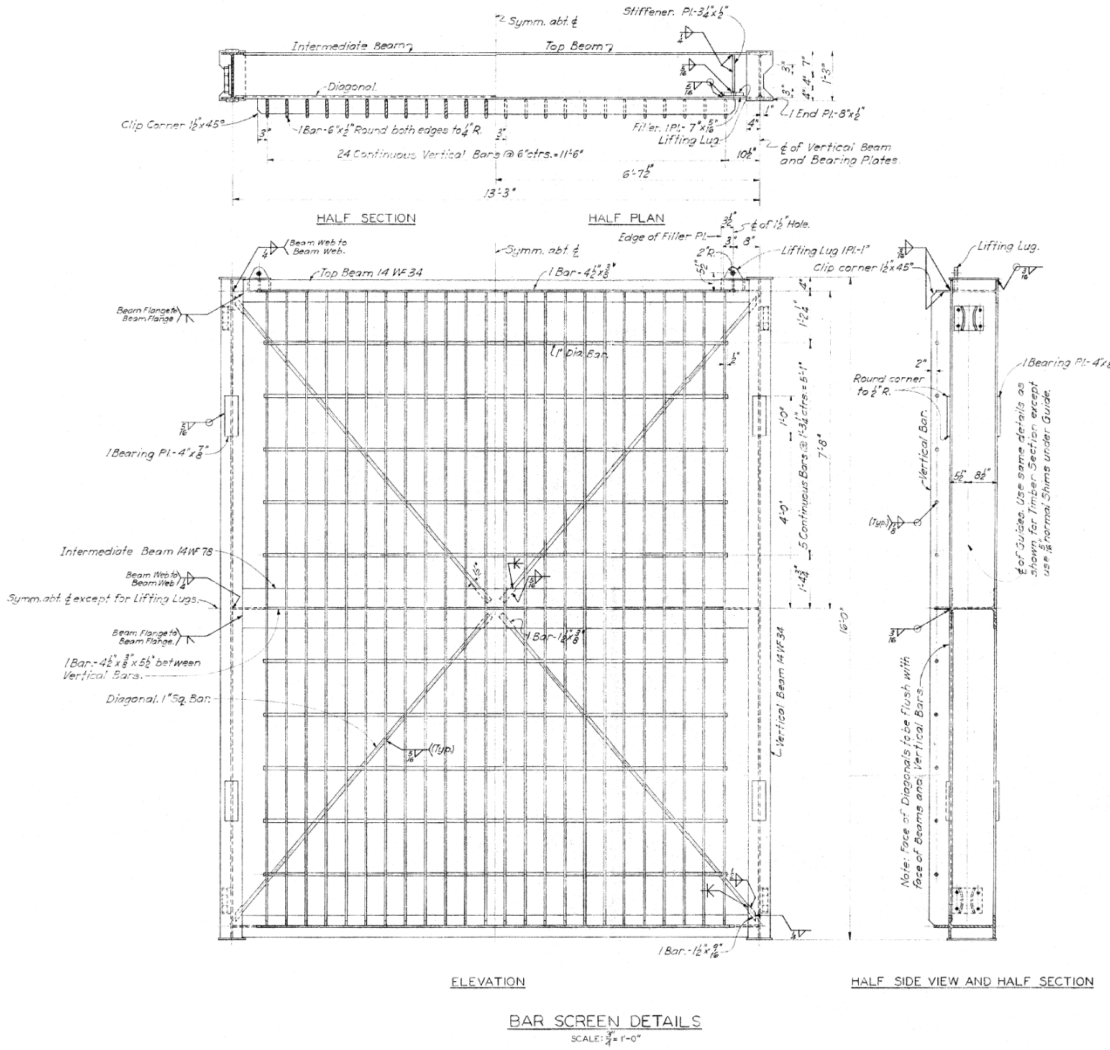


Figure 3: Details of Original Steel Trash Rack

Draft tube trash racks, typically installed in pumped-storage plants, are subjected to significant hydraulic forces. The manufacturer of the upgraded Taum Sauk runners, American Hydro Corporation (now Weir American Hydro) confirmed that their CFD modeling showed the failure location as the region of highest velocities during generation.

The hydro industry has experienced a significant number of trash rack failures, primarily failures at pumped-storage plants due to flow-induced vibrations. In October 1979, the American Society of Civil Engineers (ASCE) organized the Task Committee on Design and Performance of Reversible Flow Trashracks for the primary purpose of preparing a state-of-the-art paper on the design of trash racks for reversible flows. The resulting publication, *Hydraulic Design of Reversible Flow Trashracks*, provides best practice guidance for trash rack design [ASCE, 1993].

Failure Forensics

Figure 4 shows one of the failed sections of the draft tube trash racks. Additional inserts provide detailed photographs of a typical failure surface for the lower end of the failed portion of the rack (insert on the right-hand side in the figure) and several bars for the upper end of the failed portion (insert on the left-hand side in the figure). A preliminary examination of the failure surfaces suggested that the failure to the rack section may have occurred in three phases. Initially, fatigue cracks propagated from both sides of the lower ends of the vertical bars, likely due to excitation from flow-induced vibrations. Eventually, the fatigue cracks met in the middle of the bars, and the lower ends of the bars were sufficiently weakened to allow detachment of the bars at the bottom. Presumably, hydraulic forces acting on the detached portion of the trash rack swept the failed section downstream, quickly tearing away the upper portion of the bars. Subsequent metallurgical evaluations identified the initial failure as corrosion-accelerated fatigue.

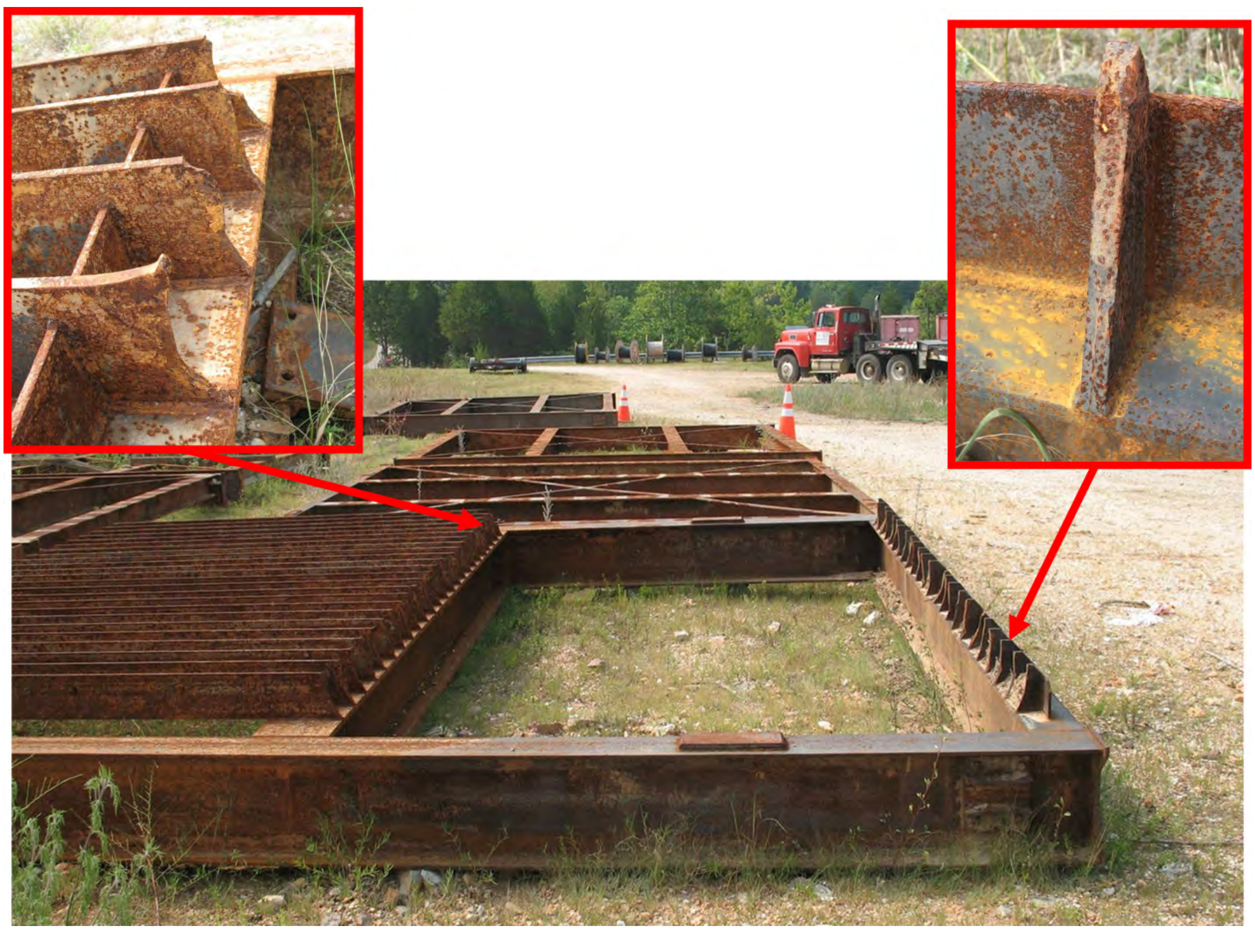


Figure 4: Failed Section of Trash Rack and Details

As shown in Figure 5, modal analysis testing was performed by Structural Technology Corporation (STC) on an undamaged trash rack. Results were used to identify likely natural frequencies of the trash rack that could be excited by flow-induced vibrations. The modal analysis testing utilized the impact-response technique [Ewins, 1984], with frequency response functions measured by tri-axial accelerometers (Figure 5C) at 119 measurement points (Figure 5B) with 114 impact points (Figure 5A). Modal frequencies and shapes for the trash rack were computed from the resulting impact-response transfer functions (Figure 5D) using proprietary STC software.

A. Modal Analysis Testing Underway

B. Response Accelerometers

C. View of Tri-axial Accelerometer

D. Instrumentation for Data Analysis

Figure 5: Modal Analysis Testing of Undamaged Trash Rack

Excitation from vortex shedding can cause either forced vibrations at the vortex shedding frequency or hydroelastic vibrations. Trash racks typically experience hydroelastic vibrations, where one or more natural frequencies of the trash rack interact with the vortex shedding to further organize the excitation, strengthen the excitation, and widen the velocity range over which the resonant vibrations occur [Ippen et al., 1960; Crandall et al., 1975; March and Vigander, 1979; March and Vigander, 1980; Blevins, 1984; Blevins, 1990].

Figure 6 shows ASCE's recommended nomenclature for vibration modes of trash racks [Crandall et al., 1975; March and Vigander, 1979; ASCE, 1993]. "Heave" is vertical vibration, "lateral" vibration is transverse to the flow, and "plunge" vibration is in the flow direction.

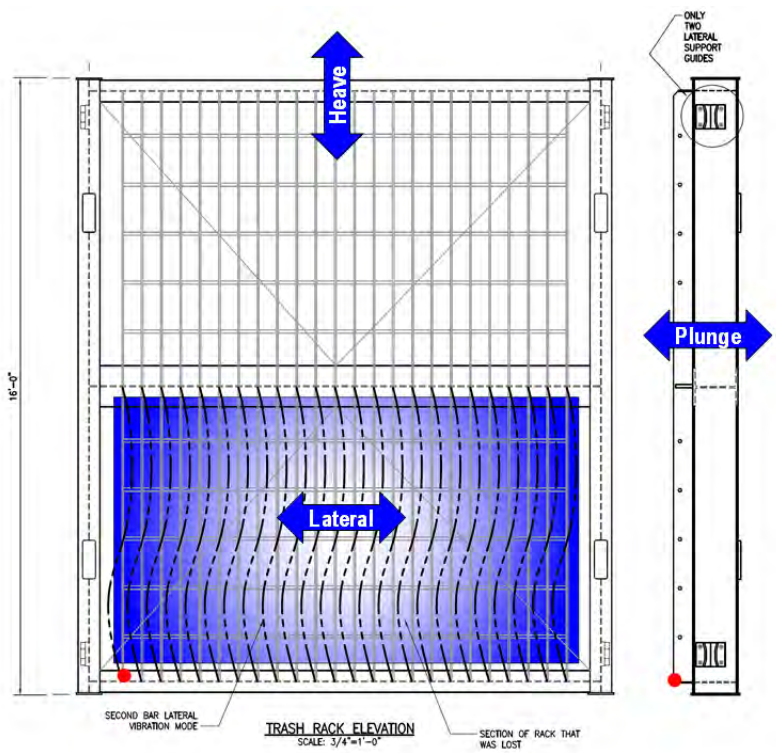


Figure 6: ASCE Nomenclature for Vibration Modes of Trash Racks

From the modal field testing, 29 vibration modes, ranging in frequency from 19 Hz to 289 Hz, were identified. To evaluate the potential for flow-induced vibrations, the measured natural frequencies and mode shapes for the trash racks were compared to vortex shedding frequencies estimated using the Strouhal Number:

$$F_{vs} = \mathbf{S} \cdot V/L$$

where

F_{vs} = Vortex shedding frequency (Hz);

$\mathbf{S}$ = Strouhal Number (dimensionless);

V = Characteristic velocity (ft/s), typically the approach velocity;

L = Characteristic length (ft), typically the bar thickness.

Over a wide range of conditions applicable to vortex shedding from trash racks, the Strouhal Number ranges from approximately 0.2 to 0.22 for rectangular members and from approximately 0.19 to 0.21 for circular members [Ippen et al., 1960; Hoerner, 1965; March and Vigander, 1979; Blevins, 1984; Blevins, 1990].

Expected vortex shedding frequencies for all of the primary elements of the original trash rack, including square bars, round rods, and rectangular bars, were computed based on assumed Strouhal Numbers and approach velocities determined from flows at the Most Efficient Load (MEL) and the maximum load. Figure 7 is a typical diagram showing correlation between the expected range of vortex shedding frequencies and the observed lateral natural frequencies for the trash rack bars. The thickness of the horizontal bars showing the lateral mode frequencies represents the small anticipated decrease in frequency associated with the added-mass effect when the trash rack is vibrating in water rather than air [March and Vigander, 1982; Blevins, 1984; Blevins, 1990]. Similar diagrams were also developed and evaluated for heave modes and plunge modes at both MEL flows and maximum flows.

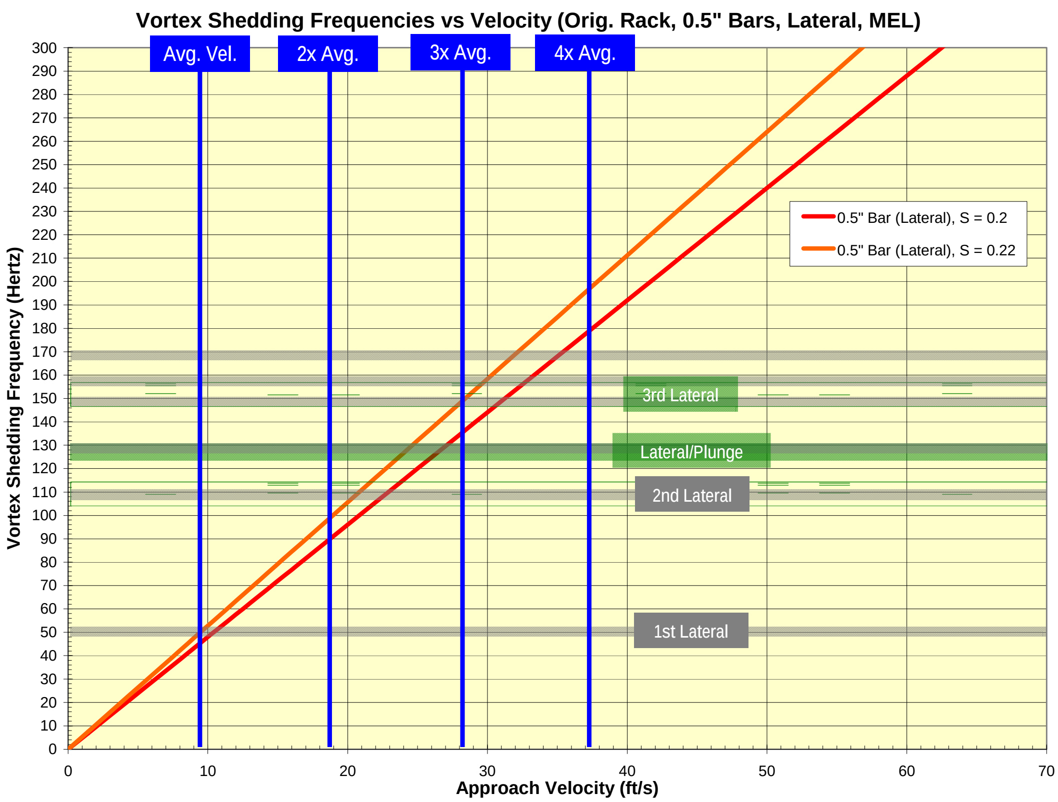
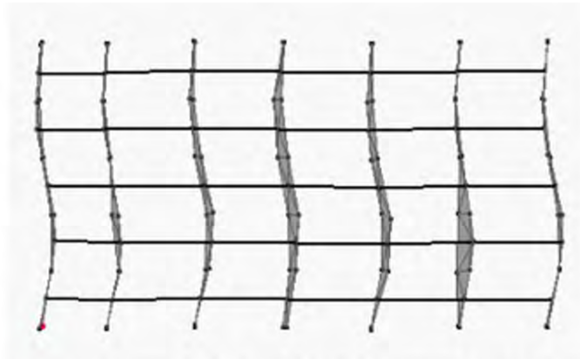


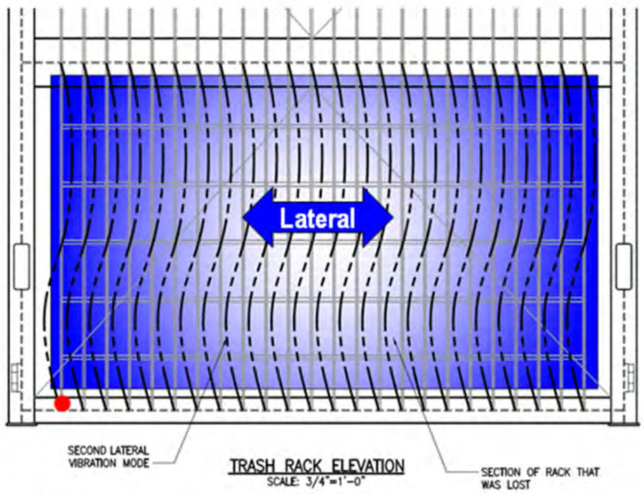
Figure 7: Correlation between Vortex Shedding Frequencies and Trash Rack Vibration Modes (Original Rack Design)

The lateral modes are displayed in Figure 7 because these modes are consistent with the fatigue cracking observed in the lower portion of the bars. The first lateral mode, shown in Figure 7 in the vicinity of 50 Hz, lines up with the vortex shedding frequency produced by the average approach velocity during normal generating. However, if this mode was responsible for the rack failure, the failure would not have been localized to the velocity "hot spot."

The second lateral mode (106.5 Hz in air) is a more likely candidate for involvement in the rack failure. The mode shape for the second lateral mode, based on the modal field tests, and a simplified schematic which superimposes the second lateral mode shape onto the missing rack section are shown in Figure 8.



A. Second Lateral Mode at 106.5 Hz (from Field Tests)



B. Simplified Schematic Showing Second Lateral Mode

Figure 8: Modal Analysis Results Showing Second Lateral Mode at 106.5 Hz

Re-design of Trash Racks

HPPi provided a preliminary trash rack design based on a previously successful design for a draft tube trash rack [Schohl and March, 1982] and design criteria developed from the forensic analysis, the ASCE task force's recommendations [ASCE, 1993], and ASME recommendations [ASME, 1996]. The design criteria incorporated the following features:

- Varied bar dimensions and spacing to minimize effects of compounding stimuli from vortex shedding on adjacent bars;
- Increased bar thickness to increase stiffness;
- Increased section dimensions and weld geometry for design flows and trash loading;
- Minimized cross section area to limit effects on unit performance.

HDR performed static and dynamic finite element analyses (FEA) on the preliminary design, and HPPi and HDR collaborated in iteratively refining and improving the design. Design changes resulting from the FEA results and a constructability review were incorporated into the design drawings and the fabrication specification. The final design is shown in Figure 9. Typical results from the FEA dynamic analyses are shown as modal frequencies in the correlation diagram of Figure 10, which provides results for lateral vibration modes. Similar diagrams were also developed and evaluated for heave modes and plunge modes at both MEL flows and maximum flows.

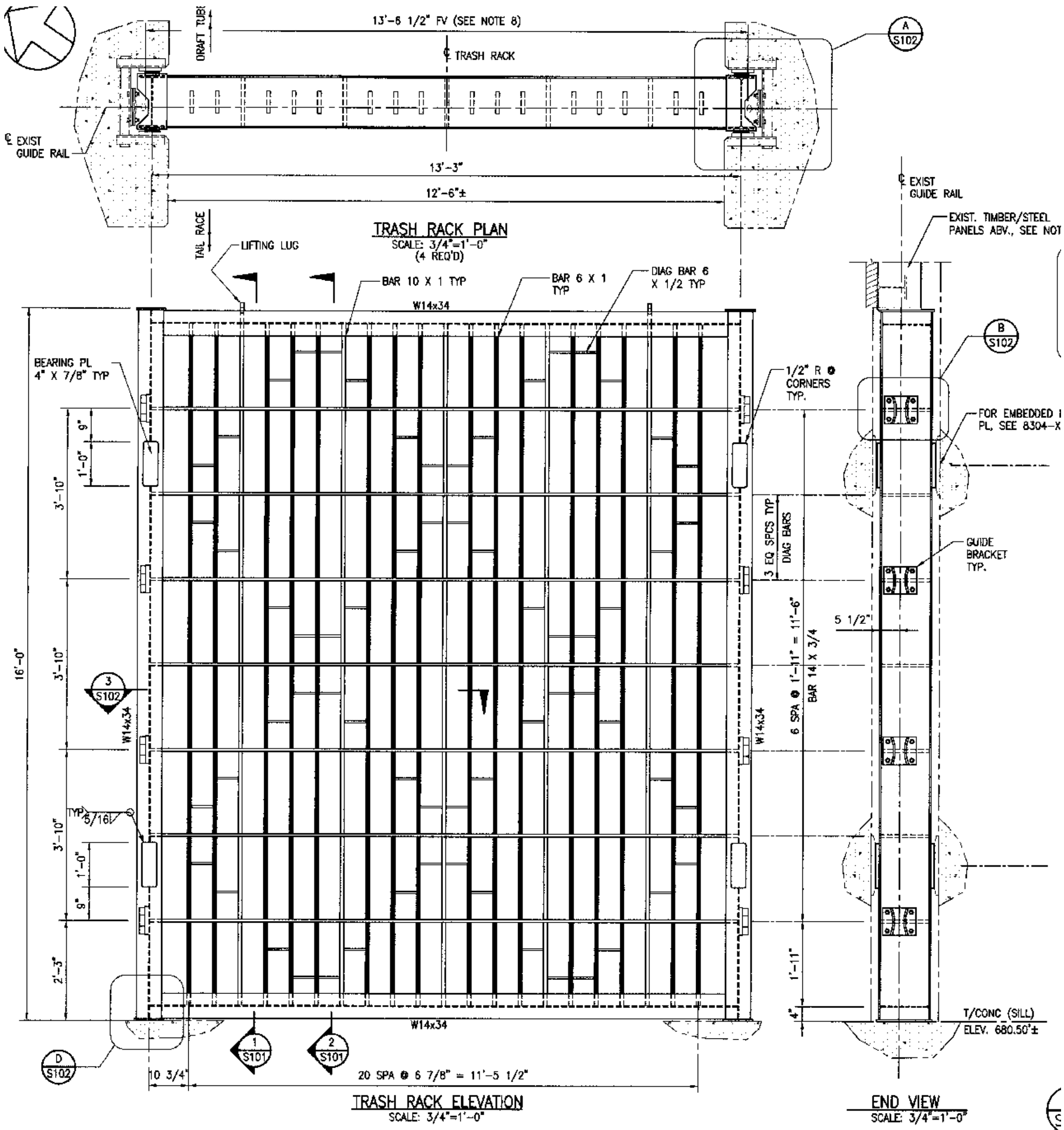


Figure 9: Design of New Trash Rack

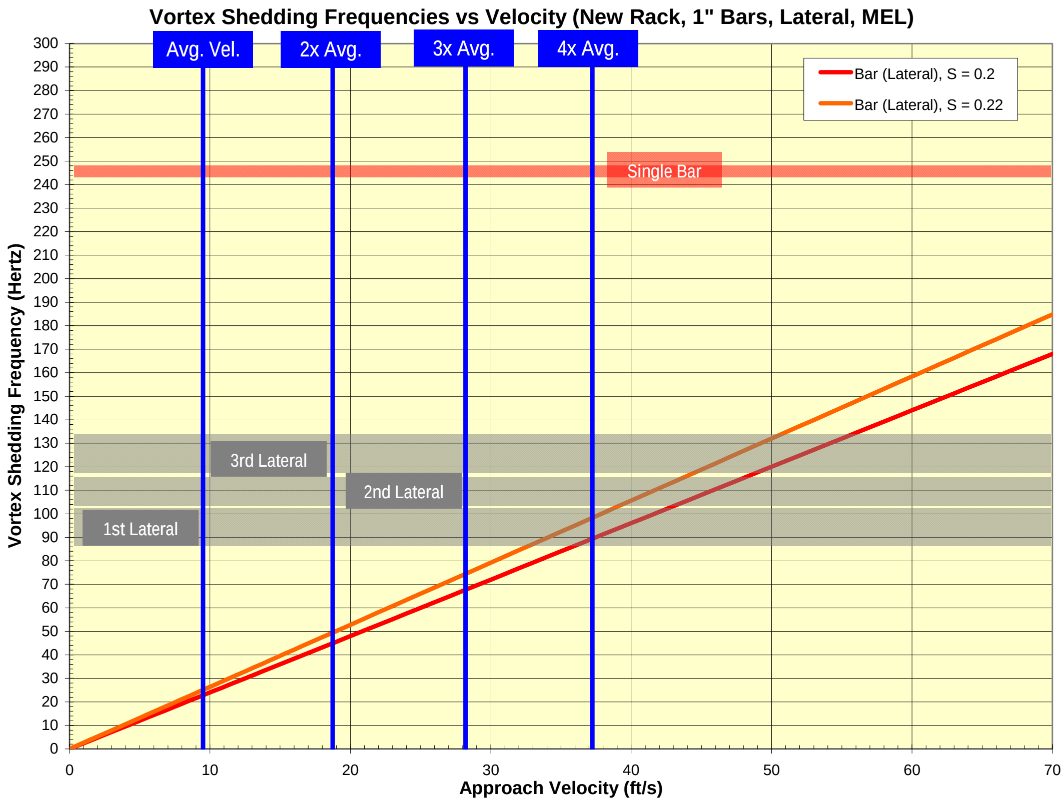


Figure 10: Correlation between Vortex Shedding Frequencies and Trash Rack Vibration Modes (New Rack Design)

Fabrication of New Trash Racks

A local steel fabricator was selected from several bidders. Work was monitored and inspected throughout the fabrication process to ensure quality, and the fabrication proceeded smoothly. Figure 11 shows one of the new racks in the fabrication shop.

Experience to Date

The new trash racks were returned to service in the Spring of 2010 (see Figure 12 and Figure 13). The Taum Sauk units have been in operation for 27 months. Cursory inspections of the draft tube trash racks have been performed by divers during unit outages. No failures or indications of other problems have been found. In March 2012, divers performed an extensive underwater inspection of the trash racks. All section members were inspected and visually confirmed by camera (see Figure 14). No degradation, indications of cracking, or other problems were found.

Figure 11: New Trash Rack in Fabrication Shop

Figure 12: New Trash Rack during Unloading at Plant

Figure 13: New Trash Rack during Installation at Plant

Figure 14: Typical View during Trash Rack Inspection

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